2009

Managing water use from forest plantations

Jerome K. Vanclay
Southern Cross University

Publication details

Pre-print of: Vanclay, JK 2009, 'Managing water use from forest plantations', *Forest Ecology and Management*, vol. 257, no.2, pp. 385-389.
Forest Ecology and Management home page available at www.elsevier.com/locate/foreco
Publisher's version of article available at http://dx.doi.org/10.1016/j.foreco.2008.09.003

Forest Ecology and Management, 257:385-389 (2008).

Managing water use from forest plantations

Jerome K Vanclay

Southern Cross University

PO Box 157 Lismore NSW 2480

Tel +61 2 6620 3147, Fax +61 2 6621 2669, JVanclay@scu.edu.au

Abstract

Tree plantations have developed a reputation for excessive water use, with age commonly used as an explanatory variable to predict water loss – but many factors have the potential to affect plantation water use, and few of these alternatives have been considered. Changes in forest cover may be correlated with other environmental changes that may affect precipitation, transpiration, and runoff, indicating that more thorough investigation is required in both field and simulation studies. Several factors influencing water use by plantations are amenable to management control, so there is scope to design and manage forest plantations deliberately for water use efficiency. Research is needed to elucidate the relative contributions of forests and grasslands to atmospheric moisture; the influence of vegetation on the distribution of rainfall; the effect of air turbulence from plantation edges, firebreaks and streamlines; the potential to modify atmospheric coupling of forest plantations through plantation design, the use mixed species plantations, and by softening hard edges by thinning and pruning plantation edges.

Key words: Runoff, infiltration, evapotranspiration, roughness, atmospheric coupling

Introduction

Water use by plantations has received prominent attention in many circles in recent years (Andreassian, 2004; Farley et al., 2005; Jackson et al., 2005; Brown et al., 2007; Dijk and Keenan, 2007; Dijk et al., 2007; Dye and Versfeld, 2007), but the evidence presented remains equivocal. Much of the discussion in Australia (e.g., Keenan et al., 2006) accepts the current paradigm without sufficient regard for the uncertainties. This paper re-examines some of these assumptions, highlights issues that warrant further research, and draws attention to ways that forests may be managed to minimize water loss. This paper makes no attempt to comprehensively present all the 'plantations versus water' literature which is well covered in recent reviews (e.g., Vertessy et al., 2001; Brown et al., 2005; Farley et al., 2005; Jackson et al., 2005; Benyon et al., 2007; Dijk and Keenan, 2007). Instead, it seeks to complement those reviews by re-examining equivocal elements and offering alternative interpretations that warrant further investigation.

Literature

Recent reviews (Vertessy et al., 2001; Brown et al., 2005; Farley et al., 2005; Jackson et al., 2005; Benyon et al., 2007; Dijk and Keenan, 2007) have postulated that water yield from afforested catchments declines with increasing plantation age, specifically through the relationship with leaf area index (Watson et al., 1999). In Australia, the correlation between age of regrowth and water yield is often attributed to Kuczera (1987), but others had earlier noted a correlation between the basal area of regrowth and water yield (e.g. Kovner 1956). This relationship with forest age appeals to many people because the assumed trend reflects the typical pattern of tree growth and invites the implicit assumption is that faster growth must require more water (e.g., Spring et al., 2005). However, very little of the water used by plantations is assimilated as carbohydrate (Kozlowski, 1982); most is transpired to the atmosphere as water vapour. This popular view is contrary to local knowledge in many places (Wilk, 2000), and overlooks the alternative explanation that tall dense canopies have strong aerodynamic coupling and high evapotranspiration (Goldberg and Bernhofer, 2001). So the question that remains is why hydrological dynamics change after plantation establishment, and what alternative explanations warrant exploration. In many cases, this question is posed in the context of afforestation of agricultural land, but it also applies in analogous situations (regrowth following wildfire or timber harvesting) and the converse situation of deforestation.

One possibility is that it is not the tree plantation *per se*, but other aspects of the change in land use that influences hydrology and changes the pattern of runoff. For instance, it has long been known that grazing causes soil compaction and reduces infiltration (e.g., Dunford, 1949; Rauzi and Hanson, 1966; Trimble and Mendel, 1995; Mwendera and Mohamed Saleem, 1997; Hiernaux et al., 1999; Chandler, 2006), and that the removal of grazing can lead to a reduction in runoff (e.g., Hamza and Anderson, 2005). In addition, most plantation establishment involves actively modifying the soil to reduce runoff and improve infiltration (Evans and Turnbull, 2004; Ilstedt et al., 2007). It is logical that these changes to the soil may affect hydrology and affect both base and peak flows (Guillemette et al., 2005; Waterloo et al., 2007). This effect would appear to operate at a time-scale commensurate with the alleged age-dependent water use trend, but relatively few publications have examined the potential interaction of land use history on the runoff (e.g., Ferreira et al., 2005; Zimmermann et al., 2006).

Another possible explanation arises from weaknesses in paired catchment studies, which remain the mainstay of many hydrology studies. Many paired catchment studies rely on simplistic assumptions of rainfall distribution to infer the rainfall in both catchments, and may lack sufficient replication or control of treated and untreated watersheds (Blackie and Robinson, 2007). Many limitations have been examined (e.g., Blöschl et al., 2007; Brown et al., 2005; Cosandey et al., 2005; Lane et al., 2005; Liu et al. 2003; Stednick, 1996; Watson et al., 2001) but the possibility that rainfall patterns may change after de- or re-forestation in one of the catchment pairs is rarely entertained. Evidence suggests that land use can influence rainfall within substantial neighbourhoods (Anthes, 1984; Trenberth, 1998, 1999; Bornstein and Lin, 2000; Pielke, 2001; Shepherd and Burian, 2003; Bruijnzeel 2004; D'Almeida et al., 2007), and that regional recycling of rainfall can be significant (Raddatz, 2000; Bosilovich and Schubert, 2001). Empirical reports indicate that deforestation in the Amazon (Nobre et al., 1991; Rocha, 1996; Moreira et al., 1997; Marengo, 2006; Trancoso, 2007) and in equatorial Africa (Kunstmann and Jung, 2003; Roy et al., 2005) has changed local climate, and theoretical studies support this notion (Makarieva et al., 2006; Makarieva and Gorshkov, 2007). So it is likely that paired catchments may not be independent (in an experimental sense) and may affect the rainfall in the adjacent pair (Pielke et al., 2007). Reviews have not eliminated the possibility that rainfall may emulate the "tragedy of the commons" (Hardin, 1968) with forested catchments transpiring the most moisture while non-forested catchments receive a disproportionate share of rainfall. This may occur in situations where precipitation originates as evapotranspiration (rather than as evaporation from open water), and may confound simple paired-catchment comparisons.

Several studies in Australia (e.g., Peel et al., 2000, 2003) rely on the Macaque model (Watson et al., 1999), a model with the unconventional characteristic that the two largest flows (precipitation and transpiration) are exogeneous: precipitation falls from and transpiration disappears into the sky, with no attempt to examine possible connectivity of feedback and rainfall recycling, which may be substantial (Brubaker et al., 1993; Burde and Zangvil, 2001; D'Almeida et al., 2006). Other researchers have commented on the significance of this feedback at various scales (e.g., Makarieva et al., 2006; Molen et al., 2006; Gordon et al., 2008). This deficiency casts doubt on the reliability of some predictions.

Managing forests to minimize water loss

This wide-ranging review of the literature offers sufficient evidence to challenge the accepted paradigm that the reduction in runoff is due to plantation age, to support the possibility of alternative explanations, and to suggest the possibility to manage plantations to reduce water loss. How then, might plantations be managed to reduce water use?

The Penman-Monteith equation is a well-established approach to estimating plant water use (Irmak et al., 2005; Cleugh et al., 2007), and it is easy to conduct a few simple simulations to show that water use by a crop depends strongly on windspeed and atmospheric coupling (e.g., Díaz et al., 2007), both of which may be influenced through forest management. However, few studies of plantation water use take windspeed into account (e.g., Cannell, 1999). Several authors (e.g., Andreassian, 2004; Blanken and Black, 2004; Buytaert et al., 2007) have observed the correlation between leaf area index and coupling. Blanken and Black (2004) observed that seasonal changes in the structure of deciduous forests had a significant effect on coupling and canopy conductance, and Schellekens (2000; Schellekens et al., 2000) has observed the effect of hurricane damage in modifying the canopy roughness and transpiration of tropical forests. The utility of wind breaks has long been recognized in the horticultural and agricultural sectors (Kort, 1988; Cleugh, 1998), but forest managers appear to have neglected the possibility to incorporate windbreaks into their plantation design, despite evidence that transpiration is greater at plantation edges (Taylor et al., 2001). Tree species vary greatly in their ability to regulate water loss through stomatal control (Jones, 1998; Whitehead and Beadle, 2004) and canopy characteristics (Komatsu et al., 2007), and a carefully chosen species could provide an effective windbreak to reduce water loss from timber plantations.

Another possibility to control water use is to design the plantation canopy to maximize decoupling by managing canopy roughness (Calder, 1997; Hollinger et al., 2002) and air turbulence induced by abrupt plantation edges and firebeaks (Zhang et al., 2007). There are some indications (e.g., Forrester, 2007) that mixed species plantings may have a canopy structure that is less coupled to the atmosphere, and which may thus reduce transpiration. This may help explain some of the “many unresolved issues about water use from fragmented, heterogeneous vegetation” (Roberts, 2007; similar observation by Bruijnzeel, 2004). It seems likely that plantation prescriptions requiring that streamlines remain unplanted may be counter-productive (e.g., FIFWA, 2006; requires 6 m buffer from watercourse), because it seems possible that the turbulence induced by the irregular canopy may lead to greater water losses than if water courses were planted with selected native species.

Research needs

This review has highlighted several research needs:

- Where does rain come from: what is the relative importance of moisture transpired from vegetation and evaporated from the sea? What are the relative roles of forests and grasslands in contributing to atmospheric moisture? These questions can be examined using stable isotope analysis of rainwater (Gat, 1996; Moreira et al. 1997; Helliker and Ehleringer, 2000; Wang and Yakir, 2000; Darling and Talbot, 2003; Yepez et al., 2003; Yang et al., 2005; Farquhar et al. 2007).
- How does vegetation affect the distribution of rainfall, and can rainfall be influenced through vegetation management? This issue can be examined using existing data from weather radar (e.g. Zhijia et al., 2004). Such analyses may help improve interpretations of paired catchment studies.
- How is transpiration affected by air turbulence near plantation edges, firebreaks and streamlines? This can be examined through field studies of sap flux density (Herbst et al., 2007; Schiller et al., 2007) in existing plantations.
- Can atmospheric coupling of forest plantations be modified through plantation design, for example by using mixed species plantations to alter canopy roughness? Armbruster et al. (2004) also identified the hydrology of mixed stands as a research need. This topic is amenable to investigation with sap-flow measurements (Oltchev et al., 2002) and eddy-covariance flux

measurements (Kurpius et al., 2003; Blanken and Black, 2004; Zhang et al., 2006) in existing mixed-species plantings.

- Can existing plantations be made more water-efficient by softening hard edges by thinning and pruning edges (to increase porosity above 30%, see Minvielle et al., 2003), by planting hedges along external plantation edges to control turbulence development (Morse et al., 2002), and by re-designing the shape of planting blocks during harvesting? This is amenable to investigation through simulation modeling (Krzikalla, 2005), and through experimental modification of existing plantation edges.

Conclusion

The concern about plantations and water use expressed in recent reviews appears to have been built on a number of assumptions that have not been fully tested. Many factors have the potential to affect plantation water use, and few of these alternatives have been examined in detail. Several of these factors are amenable to management control, and there is scope to design and manage forest plantations deliberately for water use efficiency.

Acknowledgements

This paper is based on a presentation to the Northern Rivers Landcare Farming Forum held in Grafton, 30 March 2007, and benefited from discussions with several participants. Dr Esteban Jobbágy and an anonymous reviewer offered helpful comments on the draft manuscript.

References

Andreassian, V., 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology* 291:1-27.

Armbruster, M., Seegert, J., Feger, K.-H., 2004. Effects of changes in tree species composition on water flow dynamics – Model applications and their limitations. *Plant and Soil* 264:13–24.

Anthes, R.A., 1984. Enhancement of convective precipitation by mesoscale variations in vegetation covering semiarid regions. *Journal of Climate and Applied Meteorology* 23:541-554.

Benyon, R.,England, J., Eastham, J., Polglase, P., White, D., 2007. Tree water use in forestry compared to other dry-land agricultural crops in the Victorian context: Report prepared for the Department of Primary Industries Victoria to promote scientific knowledge in this area. Ensis Technical Report 159. 50 p.

Blackie, J.R., Robinson, M., 2007. Development of catchment research, with particular attention to Plynlimon and its forerunner, the East African catchments. *Hydrol. Earth Syst. Sci.* 11(1):26-43.

Blanken, P.D., Black, T.A., 2004. The canopy conductance of a boreal aspen forest, Prince Albert National Park, Canada. *Hydrol. Process*. 18:1561-1578.

Blöschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P., Szolgay, J., 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes* 21(9):1241-1247.

Bornstein, R., Lin, Q., 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment* 34: 507-516.

Bosilovich, M.G., Schubert, S.D., 2001. Precipitation recycling over the central United States diagnosed from the GEOS-1 data assimilation system. *Journal of Hydrometeorology* 2:26-35.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310:28–61.

Brown, A.E., Podger, G.M., Davidson, A.J., Dowling, T.I., Zhang, L., 2007. Predicting the impact of plantation forestry on water users at local and regional scales: An example for the Murrumbidgee River Basin, Australia. *Forest Ecology and Management* 251:82–93.

Brubaker, K.L., Entekhabi, D., Eagleson, P.S., 1993. Estimation of continental precipitation recycling. *Journal of Climate* 6:1077-1089.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* 104:185–228.

Burde, G.I., Zangvil, A., 2001. The estimation of regional precipitation recycling. Part II: A new recycling model. *Journal of Climate* 14:2509-2527.

Buytaert, W., Iñiguez, V., De Bièvre, B., 2007. The effects of afforestation and cultivation on water yield in the Andean páramo. *Forest Ecology and Management* 251:22–30.

Calder, I.R., 1997. Water use by forests, limits and controls. *Tree Physiology* 18:625-631.

Cannell, M.G.R., 1999. Environmental impacts of forest monocultures: water use, acidification, wildlife conservation, and carbon storage. *New Forests* 17:239–262.

Chandler, D.G., 2006. Reversibility of forest conversion impacts on water budgets in tropical karst terrain. *Forest Ecology and Management* 224(1-2):95-103.
Cleugh, H.A., 1998. Effects of windbreaks on airflow, microclimates and crop yields. *Agroforestry Systems* 41(1):55-84.
Cleugh, H.A., Leuning, R., Mu, Q., Running, S.W., 2007. Regional evaporation estimates from flux tower and MODIS satellite data. *Remote Sensing of Environment* 106 (2007) 285–304.
Cosandey, C., Andréassian, V., Martin, C., Didon-Lescot, J.F., Lavabre, J., Folton, N., Mathys, N., Richard, D., 2005. The hydrological impact of the Mediterranean forest: a review of French research. *Journal of Hydrology* 301:235-249.
D'Almeida, C., Vörösmarty, C.J., Marengo, J.A., Hurtt, G.C., Dingman, S.L., Keim, B.D., 2006. A water balance model to study the hydrological response to different scenarios of deforestation in Amazonia. *Journal of Hydrology* 331:125-136.
D'Almeida, C., Vörösmarty, C.J., Hurtt, G.C., Marengo, J.A., Dingman, S.L., Keim, B.D., 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *Int. J. Climatol.* 27:633–647.
Darling, W.G., Talbot, J.C., 2003. The O & H stable isotopic composition of fresh waters in the British Isles. 1. Rainfall. *Hydrology and Earth System Sciences* 7(2):163-181.
Díaz, M.F., Bigelow, S., Armesto, J.J., 2007. Alteration of the hydrologic cycle due to forest clearing and its consequences for rainforest succession. *Forest Ecology and Management* 244:32–40.
Dijk, A.I.J.M.van, Keenan, R.J., 2007. Planted forests and water in perspective. *Forest Ecology and Management* 251:1-9.
Dijk, A.I.J.M.van, Hairsine, P.B., Arancibia, J.P., Dowling, T.I., 2007. Reforestation, water availability and stream salinity: A multi-scale analysis in the Murray-Darling Basin, Australia. *Forest Ecology and Management* 251:94–109.
Dunford, E.G., 1949. Relations of grazing to runoff and erosion on bunchgrass ranges. Res. Note 7. U.S. For. Serv., Rocky Mount. For. Range Exp. Sta. Fort Collins, Colo. 2pp.
Dye, P., Versfeld, D., 2007. Managing the hydrological impacts of South African plantation forests: An overview. *Forest Ecology and Management* 251:121–128.
Evans, J., Turnbull, J.W., 2004. *Plantation Forestry in the Tropics*. Oxford University Press, 467 pp.
Farley, K.A., Jobba´gy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* 11:1565–1576.
Farquhar, G.D., Cernusak, L.A., Barnes, B., 2007. Heavy water fractionation during transpiration. *Plant Physiology* 143:11–18.
Ferreira, M.T., Aguiar, F.C., Nogueira, C., 2005. Changes in riparian woods over space and time: Influence of environment and land use. *Forest Ecology and Management* 212:145-159.
FIFWA, 2006. Code of practice for timber plantations in Western Australia. Forest Industries Federation Western Australia Inc, 71 pp. ISBN 0-9775894-0-4.
Forrester, D.I., 2007. Increasing water use efficiency using mixed species plantations of *Eucalyptus* and *Acacia*. *The Forester* 50(1):20-21.
Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Planet. Sci.* 24:225–62.

Goldberg, V., Bernhofer, C., 2001. Quantifying the coupling degree between land surface and the atmospheric boundary layer with the coupled vegetation-atmosphere model HIRVAC. *Annales Geophysicae* 19:581–587.
Gordon, L.J., Peterson, G.D., Bennett, E.M., 2008. Agricultural modifications of hydrological flows create ecological surprises. *Trends in Ecology and Evolution* 23(4):211-219.
Guillemette, F., Plamondon, A.P., Prévost, M., Lévesque, D., 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. *Journal of Hydrology* 302:137-153.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82(2):121-145.
Hardin, G., 1968. The tragedy of the commons. *Science* **162**:1243-48.
Helliker, B.R., Ehleringer, J.R., 2000. Establishing a grassland signature in veins: 18O in the leaf water of C_3 and C_4 grasses. *PNAS* 97:7894-7898.
Herbst, M., Roberts, J.M., Rosier, P.T.W., Taylor, M.E., Gowing, D.J., 2007. Edge effects and forest water use: A field study in a mixed deciduous woodland. *Forest Ecology and Management* 259(3):176-186.
Hiernaux, P., Bielders, C.L., Valentin, C., Bationo, A.,Fernández-River, S., 1999. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. *Journal of Arid Environments* 41(3):231-245.
Hollinger, D.Y., Kelliher, F.M., Schulze, E.-D., Köstner, B.M.M., 2002. Coupling of tree transpiration to atmospheric turbulence. *Nature* 371:60 – 62.
Ilstedt, U., Malmer, A., Verbeeten, E., Murdiyarso, D., 2007. The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. *Forest Ecology and Management* 251:45–51.
Irmak, S., Howell, T.A., Allen, R.G., Payero, J.O., Martin, D.L., 2005. Standardized ASCE Penman-Monteith: Impact of sum-of-hourly vs. 24-hour timestep computations at reference weather station sites. *Transactions of the ASAE* 48(3):1-15.
Jackson,R.B, Jobba´gy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl,B.A., Murray, B.C., 2005. Trading Water for Carbon with Biological Carbon Sequestration. *Science* 310:1944-47.
Jones, H.G., 1998. Stomatal control of photosynthesis and transpiration. *Journal of Experimental Botany* 49:387–398.
Keenan, R.J., Gerrand, A., Nambiar, S., Parsons, M., 2006. Plantations and Water: Plantation impacts on stream flow. Science for Decision Makers, February 2006 Revised edition. Department of Agriculture, Fisheries and Forestry, Canberra, 8 pp.
Komatsu, H., Kume, T., Otsuki, K., 2007. The effect of converting a native broad-leaved forest to a coniferous plantation forest on annual water yield: A paired-catchment study in northern Japan. *Forest Ecology and Management* 255(3-4):880-886.
Kort, J., 1988. Benefits of windbreaks to field and forage crops. *Agriculture, Ecosystems & Environment* 22:165-190.
Kovner, J.L., 1956. Evapotranspiration and water yields following forest cutting and natural regrowth. Proceedings, Society of American Foresters, Memphis TN, pp. 106-110.
Kozlowski, T.T.,1982. Water supply and tree growth. *For. Abstr.* 43:145-161.

Krzikalla, F., 2005. Numerical Investigation of the Interaction between Wind and Forest under Heterogeneous Conditions. Diploma Thesis, Institute for Hydromechanics, University of Karlsruhe, 113 pp.

Kuczera, G. 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology* 94(3-4): 215-236.

Kunstmann, H., Jung, G., 2003. Investigation of feedback mechanisms between soil moisture, land use and precipitation in West Africa. *Water Resources Systems - Water Availability and Global Change* (Proceedings of symposium HS02a held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 280, 2003.

Kurpius, M.R., Panek, J.A., Nikolov, N.T., McKay, M., Goldstein, A.H., 2003. Partitioning of water flux in a Sierra Nevada ponderosa pine plantation. *Agricultural and Forest Meteorology* 117:173–192.

Lane, P.N.J., Best, A.E., Hickel, K., Zhang, L., 2005. The response of flow duration curves to afforestation. *Journal of Hydrology* 310:253-265.

Liu, S., Leslie, L.M., Speer, M., Bunker, R., Mo, X., 2003. The effects of bushfires on hydrological processes using a paired-catchment analysis. *Meteorology and Atmospheric Physics* 86(1-2): 31-44.

Makarieva, A.M., Gorshkov, V.G., 2007. Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrology and Earth System Sciences* 11:1013-1033.

Makarieva, A.M., Gorshkov, V.G., Li, B.-L., 2006. Conservation of water cycle on land via restoration of natural closed-canopy forests: implications for regional landscape planning. *Ecol. Res*. 21: 897–906.

Marengo, J.A., 2006. On the hydrological cycle of the Amazon basin: a historical review and current state-of-the-art. *Revista Brasileira de Meteorologia* 21(3):1-19.

Minvielle, F., Marticorena, B., Gillette, D.A., Lawson, R.E., Thompson, R., Bergametti, G., 2003. Relationship between the Aerodynamic Roughness Length and the Roughness Density in Cases of Low Roughness Density. *Environmental Fluid Mechanics* 3:249–267.

Molen, M.K. van der, Dolman, A.J., Waterloo, M.J., Bruijnzeel, L.A., 2006. Climate is affected more by maritime than by continental land use change: A multiple scale analysis. *Global and Planetary Change* 54:128-149.

Moreira, M.Z., Sternberg, L.D.S.L., Martinelli, L.A., Victoris, R.L., Barbosa, E.M., Bonates, L.C.M., Nepstad, D.C., 1997. Contribution of transpiration to forest ambient vapour based on isotopic measurements. *Global Change Biology* 3:439-450.

Morse, A.P., Gardiner, B.A., Marshall, B.J., 2002. Mechanisms controlling turbulence development across a forest edge. *Boundary-Layer Meteorology* 103: 227–251.

Mwendera, E.J., Mohamed Saleem, M.A., 1997. Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in the Ethiopian highlands. *Soil Use and Management* 13 (1):29–35.

Nobre, C.A., Sellers, P.J., Shukla, J., 1991. Amazonian deforestation and regional climate change. *Journal of Climate* 4:957-988.

Oltchev, A., Cermak, J., Nadezhdina, N., Tatarinov, F., Tishenko, A., Ibrom, A., Gravenhorst, G., 2002. Transpiration of a mixed forest stand: field measurements and simulation using SVAT models. *Boreal Environment Research* 7:389-397.

Peel, M., Watson, F., Vertessy, R., Lau, A., Watson, I., Sutton, M., Rhodes, B., 2000. Predicting the water yield impacts of forest disturbance in the Maroondah and Thomson catchments using the Macaque model. CRC for Catchment Hydrology, Technical Report 00/14. 82 pp.

Peel, M.C., Watson, F.G.R., Vertessy, R.A., 2003. Modelling impacts of land use change on low flows in the North Esk River using the Macaque model. Proceedings, MODSIM International Congress on Modelling and Simulation, pp. 849-854.

Pielke, R.A., 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* 39(2):151-177.

Pielke, R.A., Adegoke, J., Beltrán-Przekurat, A., Hiemstra, C.A., Lin, J., Nair, U.S., Niyogi, D., Nobis, T.E., 2007. An overview of regional land-use and land-cover impacts on rainfall. *Tellus* 59B:587-601.

Raddatz, R.L., 2000. Summer rainfall recycling for an agricultural region of the Canadian prairies. *Canadian Journal of Soil Science* 80(2):367-373.

Rauzi, F., Hanson, C.L., 1966. Water intake and runoff as affected by intensity of grazing. *Journal of Range Management* 19(6):351-356.

Roberts, J., 2007. The role of plant physiology in hydrology: looking backwards and forwards. *Hydrol. Earth Syst. Sci.* 11(1):256-269.

Rocha, H.R.D., Nobre, C.A., Bonatti, J.P., Wright, I.R., Sellers, P.J., 1996. A vegetation-atmosphere interaction study for Amazonia deforestation using field data and a 'single column' model. *Quarterly Journal of the Royal Meteorological Society* 122(531A):567-594.

Roy, S.B., Walsh, P.D., Lichstein, J.W., 2005. Can logging in equatorial Africa affect adjacent parks? *Ecology and Society* 10(1): 6.

Schellekens, J., 2000. Hydrological processes in a humid tropical rain forest: a combined experimental and modelling approach. Academisch Proefschrift, Vrije Universiteit, Amsterdam, 172 pp.

Schellekens, J., Bruijnzeel, L.A., Scatena, F.N., Bink, N.J., Holwerda, F., 2000. Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. *Water Resources Research* 36(8):2183-2196.

Schiller, G., Cohen, S., Ungar, E.D., Moshe, Y., Herr, N., 2007. Estimating water use of sclerophyllous species under East-Mediterranean climate III. Tabor oak forest sap flow distribution and transpiration. *Forest Ecology and Management* 238(1-3):147-155.

Shepherd, J.M., Burian, S.J., 2003. Detection of urban-induced rainfall anomalies in a major coastal city. *Earth Interactions* 7(6):1-17.

Spring, D.A., Kennedy, J.O.S., MacNally, R., 2005. Optimal management of a forested catchment providing timber and carbon sequestration benefits: Climate change effects. *Global Environmental Change* 15:281–292.

Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176:79-95.

Taylor, P.J., Nuberg, I.K., Hatton, T.J., 2001. Enhanced transpiration in response to wind effects at the edge of a blue gum (*Eucalyptus globulus*) plantation. *Tree Physiology* 21:403–408.

Trancoso, R., Tomasella, J., Silva, R.D.C.D., Monteiro, M.T.F., Rodriguez, D.A., Cuartas L.A., 2007. Hydrological impacts of deforestation in small catchments in Brazilian Amazonian. 21st Conference on Hydrology, Session J1.2.

Trenberth, K.E., 1998. Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change. *Climatic Change* 39: 667–694.

Trenberth, K.E., 1999. Atmospheric moisture recycling: Role of advection and local evaporation. *Journal of Climate* 12:1368–1381.

Trimble, S.W., Mendel, A.C., 1995. The cow as a geomorphic agent - A critical review. *Geomorphology* 13(1-4):233-253.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K., 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. *Forest Ecology and Management* 143:13-26.

Wang, X.-F., Yakir, D., 2000. Using stable isotopes of water in evapotranspiration studies. *Hydrol. Processes* 14:1407–1421.

Waterloo, M.J.,. Schellekens, J., Bruijnzeel, L.A., Rawaqa, T.T., 2007. Changes in catchment runoff after harvesting and burning of a Pinus caribaea plantation in Viti Levu, Fiji. *Forest Ecology and Management* 251:31–44.

Watson, F.G.R., Vertessy, R.A., Grayson, R.B., 1999. Large-scale modelling of forest hydrological processes and their long-term effect on water yield. *Hydrological Processes* 13(5):689-700.

Watson, F., Vertessy, R., McMahon, T., Rhodes, B., Watson, I., 2001. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. *Forest Ecology and Management* 143:189-204.

Whirehead, D., Beadle, C.L., 2004. Potential regulation of productivity and water use in *Eucalyptus*: a review. *Forest Ecology and Management* 193(1-2):113-140.

Wilk, J., 2000. Local perceptions about forests and water in two tropical catchments. *GeoJournal* 50:339–347.

Yang, M., Yao, T., Wang, H., Tian, L., Gou, X., 2005. Estimating the criterion for determining water vapour sources of summer precipitation on the northern Tibetan Plateau. *Hydrological Processes* 20(3):505-513.

Yepez, E.A., Williams, D.G, Scott, R.L., Lin, G., 2003. Partitioning overstory and understory evapotranspiration in a semiarid savanna woodland from the isotopic composition of water vapor. *Agricultural and Forest Meteorology* 119:53–68.

Zhang, G., Thomas, C., Leclerc, M.Y., Karipot, A., Gholz, H.L., Binford, M., Foken, T., 2007. On the effect of clearcuts on turbulence structure above a forest canopy. *Theoretical and Applied Climatology* 88(1-2):133-137.

Zhijia, L., Wenzhong, G., Jintao, L., Kun, Z., 2004. Coupling between weather radar rainfall data and a distributed hydrological model for real-time flood forecasting. *Hydrological Sciences Journal* 49(6):945-958.

Zimmermann, B., Elsenbeer, H., De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic properties: Inplications for runoff generation. *Forest Ecology and Management* 222:29-38.